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Environmental assessment of black locust (*Robinia pseudoacacia* L.)-based ethanol as potential transport fuel

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Abstract
Purpose Lignocellulosic ethanol has received special research interest, driven by concerns over high fuel prices, security of energy supplies, global climate change as well as the search of opportunities for rural economic development. A well-to-wheel analysis was conducted for ethanol obtained from black locust (*Robinia pseudoacacia* L.) by means of the life cycle assessment (LCA) methodology. This study assesses the environmental profile of using ethanol in mixtures E10 and E85 as transport fuel in comparison with conventional gasoline (CG). In addition, the best model of black locust cultivation was analysed under an environmental point of view.
Methods The standard framework of LCA from International Standards Organisation was followed. To compare the environmental profiles, the study addressed the impact potentials taking into account the distance travelled by vehicles with the fuel tank full of CG. The product system includes all the processes involved from the black locust cultivation to the final use of fuels in a vehicle. The transport of all the chemicals and products is also included in the system boundaries.
Results According to the results, fuel ethanol derived from black locust biomass may help to reduce the contributions to global warming, acidification, eutrophication and fossil fuels use specifically due to the low input production regime of the agricultural stage. These reductions would be increased with the increasing ratio of ethanol in the blend. Moreover, the use of lignin, biogas and other solid waste as fuel to meet the energy requirements of the plant, positively contribute to the environmental profile of cellulosic ethanol. On the contrary, ethanol blends are less environment friendly that CG in terms of photochemical oxidants formation. The cultivation of black locust following a low-input production regime, without agrochemicals application and extra irrigation is an important reason for the environmental improvement.
Conclusions Efforts should be made to promote the production of black locust according to principles of sustainable cultivation. Moreover, technological development in ethanol production could help to improve the environmental profile in the life cycle of ethanol-based fuels. It could be interesting to develop a strategic planning which allows identifying the potential regions not only in Italy but also in other European countries in order to increase the black locust biomass yield. The cultivation of short rotation forestry and/or short rotation coppices under low-input regimes presents potential environmental benefits and advantages for the future of second-generation ethanol production in Europe.

Keywords Black locust · Life cycle assessment (LCA) · Low-input regime · Second-generation ethanol · Short rotation coppice (SRC) · Short rotation forestry (SRF)

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1 Introduction

Current dependence on oil for energy and chemicals production, together with the climate change caused by fossil fuel, demands a vast amount of natural resources and fuels. This results in massive emissions of greenhouse gases (GHG) as well as the progressive depletion of non-renewable resources (Gomes and Muylaert de Araújo 2009). Therefore, the increase in energy consumption and current dependence on crude oil to meet energy demands have motivated more and more support for the use of renewable energies. In this context, several energy scenarios and policy objectives indicate a growing increase in the production and use of biomass resources as an energy source (van Dam et al. 2009), considering the biomass as the major contributor in the future supply of energy, chemicals and materials (Jørgensen et al. 2007).

Nowadays, 40% of the total energy consumption worldwide is linked to non-renewable liquid fuels such as gasoline and diesel and transport is almost fully dependent on these kinds of fuels (Tan et al. 2008). The impact of the substitution of conventional transportation fuels by biofuels on GHG emissions is subject of fierce debate. Therefore, it is important to verify the potential environmental performance of the biofuels in comparison with that of fossil fuels. Life cycle assessment (LCA) studies come to diverse conclusions derived from differences in data quality, the setting in which production is assumed to take place, the method used to account for co-products and the assumptions on changes of above- and belowground biomass, soil organic carbon, litter and dead wood due to direct land-use change (Hoefnagels et al. 2010). In addition, the performance of biofuels on aspects such as GHG emissions and fossil fuel depletion is difficult to be quantified mainly due to the large number of uncertainty, parameters and impacts as well as methodological issues (Gomes and Muylaert de Araújo 2009).

Biofuels derived from biomass have the potential of being environmentally friendly transportation fuels and they could be produced with a net negative carbon balance (Antizar-Ladislao and Turrion-Gomez 2008). This is due to the fact that CO_2 released during the biofuel production and use could be much lower than CO_2 uptaken during feedstock cultivation and biofuel production (Antizar-Ladislao and Turrion-Gomez 2008). Furthermore, usually fossil fuels are not required during ethanol production process. Tan et al. (2004) reported that coconut-based biodiesel can produce reductions of up to 109% in the CO_2 balance in comparison with the diesel. However, there is debate over the net carbon balance since it depends on factors such as the kind of biomass source, the co-products use derived from the production process and the use or not of fossil fuels to satisfy the energy requirements (ZeaChem 2001; González-García et al. 2009a). On the contrary, carbon neutral energy alternatives (such as solar, hydro and wind) have zero net carbon CO_2 emissions.

Among the various biomass fuel options, lignocellulosic ethanol has received special research interest, driven by concerns over high fuel prices, security of energy supplies, global climate change as well as the search of opportunities for rural economic development. Liquid biofuels, especially ethanol, provide one of the few options for fossil fuels substitution in the short-to-medium term and are strongly promoted by the European Union (Directive 2003/30/EC; Gomes and Muylaert de Araújo 2009; Hoefnagels et al. 2010). Significant efforts have been made towards the development of ethanol fermentation technology and many countries have implemented or are implementing programmes for addition of ethanol to gasoline (Aden et al. 2002; Yu and Zhang 2004; Hahn-Hägerdal et al. 2006; Antizar-Ladislao and Turrion-Gomez 2008; Sánchez and Cardona 2008). In fact, it is used in the light duty vehicle fleet in a large number of countries (Fu et al. 2003). Ethanol can be blended with gasoline (usually 10% to 85% ethanol by volume) to operate in flexible fuel vehicles (FFV) and even as 100% ethanol in dedicated vehicles (Hahn-Hägerdal et al. 2006; Macedo et al. 2008).

At present, large amounts of ethanol are produced from materials such as corn, wheat, cassava, sugarcane or sugar beet, commonly known as first-generation feedstocks, which can also be used as food and animal feed. However, a variety of biomass sources can be used for ethanol production, commonly known as second-generation feedstocks using advanced technological processes. Lignocellulosic materials show great promise as raw material for transportation fuel as they can be converted into fuels and chemicals by either biochemical or thermochemical processes; additionally, they are abundant and economically viable (Hess et al. 2007). Examples of feedstocks include agricultural and wood residues, organic wastes and energy crops such as short rotation coppices (SRC), short rotation forestry (SRF), winter cover crops or perennial grasses, which could have substantially more positive environmental impact than the production of corn, soy or other annual crops (Herrera 2006).

Lignocellulosic feedstocks are the largest sources of hexose (C-6) and pentose (C-5) sugars (Kaparaju et al. 2009). However, these materials are more complex substrates than starch and sugar-based materials since they are composed of carbohydrate polymers which are not readily available for hydrolysis and subsequently, a pre-treatment stage is necessary. Highly efficient conversion of the carbohydrates in biomass to fermentable sugars is essential to obtain commercially competitive cellulosic ethanol (Kumar et al. 2009).

LCA methodology has proved to be a valuable tool for analysing environmental considerations of a product or

process that need to be part of the decision-making process towards sustainability. A number of publications are already available on LCA studies carried out to identify the environmental performance of the production of ethanol from different lignocellulosic feedstocks such as corn stover (Luo et al. 2009b), flax shives (González-García et al. 2009a), Ethiopian mustard (González-García et al. 2009b), switchgrass (Spatari et al. 2005; Bai et al. 2010), cane molasses (Nguyen and Gheewala 2008a), alfalfa stems (González-García et al. 2010a), poplar (González-García et al. 2010b) and the subsequent use of the fuel in vehicles; none of them have considered the use of black locust. Several differences have been found in the results specifically due to the lack of a commercial lignocellulosic ethanol production (Spatari et al. 2005). As general conclusion, ethanol as a liquid fuel would have environmental advantages in terms of mitigating non-renewable energy consumption and GHG emissions. On the contrary, ethanol application could have adverse effects on impact categories such as acidification and eutrophication, due to emissions related to agricultural activities such as nitrogen oxides by the use of nitrogen fertilizers.

Black locust (*Robinia pseudoacacia* L.) is a fast-growing dicotyledonous tree, native from the south-eastern United States, but it has been widely planted elsewhere in temperate North America, Europe and Asia. This tree has shown a high level of silvicultural performance and a strong ability to grow in marginal lands with degraded soils, mainly due to the fact that it has nitrogen-fixing bacteria on its root system, which allows it to grow on poor soils. Therefore, it can be grown on lands which cannot be used for food production. In recent years, this hardwood specie has been recognized as an excellent source of short cellulose fibres for papermaking (Liu and Retulainen 2004).

Black locust is receiving special attention in recent years as a potential energy crop together with other SRC/SRF crops such as willow and poplar (Gasol et al. 2010) in a low-input production regime. This regime avoids the use of agrochemicals, excluding the irrigation stage and reducing mechanical operations for weed control. The application of this regime to the mentioned crops leads to higher biomass yields and lower environmental impacts than those from annual herbaceous crops (Heller et al. 2003; Gasol et al. 2010). Other social and economic benefits of using black locust as feedstock for ethanol production are that this crop does not compete with food and feed crops, its cultivation is spread in the Mediterranean basin and its water requirement is lower than other crops such as poplar.

The chemical composition of black locust is similar to other fast-growing and short-rotation energy crops since its biomass presents a composition rich in cellulose and hemicellulose (Pinto et al. 2005). In addition, black locust could also be interesting in comparison with forest waste use with this purpose since forest waste is commonly used as raw materials in power plants (Portal Forestal 2010).

This study focuses on black locust biomass as a second-generation feedstock to produce ethanol according to a cellulosic technology scheme. The LCA model was developed for the black locust cultivation for ethanol production as well as its use as a transportation fuel in a flexi-fuel vehicle (FFV). In this study, we focus on the black locust biomass production system in Italy with two different rotation models. In particular, the analysis compares the environmental performance of ethanol in a 10% blend with gasoline (E10) and ethanol in an 85% blend with gasoline (E85) with conventional gasoline (CG) in terms of fossil fuel use, global warming, acidification, eutrophication and photochemical oxidant formation. So far, although LCA studies have been conducted to assess the environmental impacts of cellulosic ethanol from other SRC (Frederick et al. 2008; González-García et al. 2010b), no studies were found on ethanol produced from black locust biomass.

2 Goal and scope definition

2.1 Objectives

The goal of this study was to analyse the production of lignocellulosic ethanol of *Robinia pseudoacacia* L. from an environmental point of view and additionally, to compare the environmental performance of internal combustion engine automobiles fuelled with that ethanol and gasoline. The blend of 10% (*v*/*v*) ethanol with gasoline (E10) does not require engine modifications. However, the use of ethanol in large proportions (85–100%) requires modified engines. In this study, the use of FFV, which could alternatively use either pure gasoline or blends of gasoline and ethanol, was considered. Therefore, the different fuel formulations considered for comparison were gasoline (CG), E10 and E85 (85% ethanol and 15% petrol by volume), in amounts required to deliver the same amount of energy "to the wheels". Moreover, the production of the lignocellulosic biomass will be carried out under two different conditions, so the best option from an environmental point of view will be chosen.

2.2 Functional unit

The function investigated in the study is that of driving an FFV. There are different ways of defining the functional unit (FU) and the choice has an important influence on the results (González-García et al. 2009b). In addition, the choice of the FU is highly dependent on the aim of the study. In this study, the FU chosen was based on the

distance travelled by vehicles with the vehicle tank full of CG. The average fuel economy of the FFV under study when running on CG, E10 and E85 was assumed to be 15.15, 14.49 and 10.87 km/kg, respectively. If 36 kg of CG fills up the tank of an FFV, it drives for 545 km (Kim and Dale 2006; Bai et al. 2010). This distance with E10 and E85 would require about 37.6 and 50.2 kg, respectively.

2.3 Description of the system under study

All the relevant processes included in the study are shown in Fig. 1. Furthermore, those for capital goods and wastes management were also included. The production and disposal of the car were left outside of the system boundaries.

2.3.1 Agriculture production of black locust (S1)

The first step in the ethanol production is biomass cultivation (Gasol et al. 2010). Two standard hectares of black locust plantation with different rotation models and cultivated in Po Plain (Italy) were considered in this study since large areas allocated to agro forest species (such as poplar, eucalyptus and black locust) for energy purposes are located in this Italian region. Both black locust plots had a density of 1,100 plants/ha. The first one is a SRC based on a Swedish 2-year rotation model for a total of 8 years cycle. The second one is a SRF based on an American model with a 5-year rotation and a total cycle of 15 years. After 8 or 15 years, the land needs to be prepared again. One of the main characteristics of the black locust crops is that it does

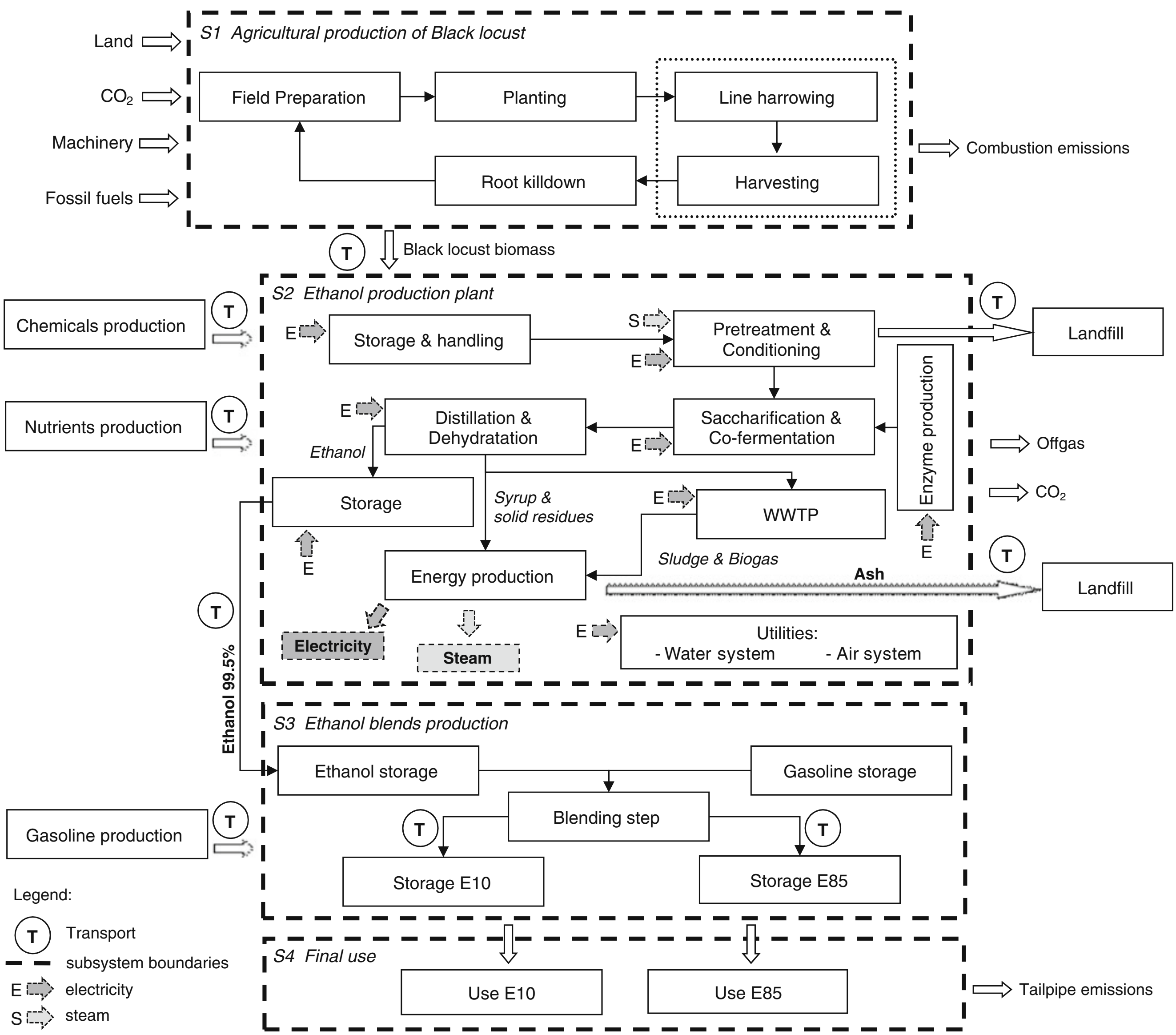


Fig. 1 System boundaries of black locust-based ethanol E10 and E85 fuels life cycle

not require high inputs of agrochemicals to assure considerable biomass production. In both plots, there is no application of fertilizers and other agrochemicals and the black locust biomass production assumed was 7.5 tonnes dry matter (0% moisture) per year in the SRC case and 9.6 tonnes dry matter per year in the SRF case, which accounts for 25 fresh tonnes (40% w.c.) every 2 years in the SRC and 80 fresh tonnes every 5 years in the case of SRF. Table 1 gives a timeline for the major operations undertaken in the black locust management (Gasol et al. 2010). In this study, we have excluded from the subsystem boundaries the natural nitrogen dynamic due to absence of available data. It is important to remark that the harvesters considered do not simultaneously harvest and chip the biomass, so the chipping step takes place in the biorefinery. In addition, CO_2 is fixed when photosynthesis occurs in black locust, which is good from the perspective of mitigating climate change. The fixation of CO_2 was estimated by the C-content in the dry matter multiplied by the stoichiometric factor 44/12, based on the assumption that the carbon in the biomass is completely taken from the air (~1.65 kg CO_2/kg dried biomass). The farmers transport to cultivate and supervise the crop was also included.

2.3.2 Ethanol production plant (S2)

In the ethanol plant, black locust biomass is chipped and converted to ethanol by means of biological conversion. The material and energy balances for ethanol production are based on the ethanol conversion technology from corn stover reported by the National Renewable Energy Laboratory (Aden et al. 2002), assuming that ethanol production efficiency is equivalent for other lignocellulosic crops (Aden et al. 2002). In this case, the conversion process was simulated and adapted to the black locust biomass composition (Table 2). The conversion of the dry biomass involves a pre-treatment stage with dilute sulphuric acid at high temperature with simultaneous saccharification (enzymatic) and co-fermentation, finishing with the distillation of the beer to separate the ethanol from the water and residual solids. The model considered in this study assumes that all sugars obtained from cellulose and hemicellulose are transformed into ethanol. The treatment of the wastewaters from distillation and evaporation condensates produces biogas. The lignin fraction present in the biomass, as well as other solids and the biogas, are used as fuel to meet all the energy requirements of the plant (electricity and steam). It is important to remark that biomass chipping step is included in the biorefinery activities and this is a high-energy-intensive process (González-García et al. 2009c). The production of the enzymes consumed in the conversion process was included within the subsystem boundaries. Transports of all consumable materials up to the plant gate and the landfill of gypsum and ashes generated in the ethanol production process were also included in this subsystem.

Table 1 Black locust field operations timeline (between parenthesis: number of repetitions)

Year	Activity SRC	Activity SRF
0	Mow, plough, disc the land, plant	
1	Line harrowing (3)	
2	Harvesting	Line harrowing (2)
3	Line harrowing (2)	–
4	Harvesting	–
5	Line harrowing (1)	Harvesting/line harrowing (2)
6	Harvesting	Line harrowing (1)
7	Line harrowing (1)	–
8	Harvesting/root killdown	–
10	–	Harvesting/line harrowing (2)
11	–	Line harrowing (1)
15	–	Harvesting/root killdown

2.3.3 Ethanol blends production (S3)

The distribution of ethanol from the ethanol plant to a gasoline station is carried out by 32 tonnes diesel lorries over an average distance of 20 km (Bai et al. 2010). The production of the gasoline as well as its transport to the gasoline station, the mixture of gasoline and ethanol to produce the blends under study (E10 and E85) and their regional storage were also included within this subsystem boundary. When pure gasoline is used as transport fuel, its delivery to a regional storage was also considered in this subsystem.

2.3.4 Final use (S4)

Tailpipe emissions derived from the combustion of fuels in a FFV were calculated according to the economy fuels and the functional unit selected. Manufacture, maintenance and disposal of the FFV were excluded from the subsystem boundaries.

2.4 Data sources

The most effort consuming step in the execution of LCA studies is the collection of inventory data in order to build the life cycle inventory (LCI). Moreover, high-quality data is essential to make a reliable evaluation. The procedure for LCI of the system under study is summarized in Table 3. Data for the study was collected

Table 2 Assumed composition on dry basis of feedstock delivered to the refinery gate (adapted from Pinto et al. (2005))

Component	Weight fraction
Cellulose	0.465
Hemicellulose	0.133
Lignin	0.271
Acetate	0.013
Ash	0.002
Others	0.116
Total	1.00

from different sources: field data, interviews, research reports and literature. Description of the hypotheses regarding transport activities in the ethanol life cycle is shown in Table 4. The inventory table of the global process is shown in Table 5. Emissions from the production of capital goods (such as general industrial machinery and equipments, tractors, etc) were taken from the EIPRO database (Tukker et al. 2006) and inventory data for production of chemicals was taken from Althaus et al. (2007). Inventory data for the landfill process was taken from Doka (2007). All the enzyme requirements in the ethanol plant were produced in the own plant and inventory data were taken from Wooley et al. (1999).

2.5 Allocation procedure

Allocation (partitioning of input or output flows of a unit process to the product under study) is one of the most critical issues in life cycle assessment. In this study, allocation procedure was not compulsory because black locust crops produce only lignocellulosic biomass. Allocation was also avoided for the ethanol plant because all the electricity produced from wastes is consumed in the ethanol and enzyme production processes. Solid residues generated in the plant, such as gypsum from distillation and ashes from boilers, are sent to landfill and were considered as wastes. As a result, all the environmental burdens for S2 were allocated to cellulosic ethanol.

3 Results

Life cycle impact assessment was conducted using characterisation factors from CML methodology (CML 2010). The potential impact categories considered in the analysis were: climate change (CC), photochemical oxidants formation (PO), acidification (AC) and eutrophication (EP). In addition, the analysis was completed with the evaluation of energy use according to the indicator of fossil fuels use (FF). Special attention was paid to the GHG emissions and fossil

Table 3 Data sources for the life cycle inventory of black locust-based ethanol production

Subsystem	Data required	Data sources	Collecting method
S1	Fuel use Labour use Consumable materials and biomass transport (mode, capacity and distance) Tailpipe emissions	Research reports and literature (Gasol et al. 2009; Gasol et al. 2010), assumptions (Table 4)	Questionnaires interviews, literature review
S2	Production capacity Chemicals use Nutrients use Enzyme production Landfill operation Energy requirements Industrial equipment use Wastewater treatment plant	Research reports (Wooley et al. 1999; Aden et al. 2002; Tukker et al. 2006; Doka 2007; Althaus et al. 2007; Spielmann et al. 2007)	Literature review
	Consumable materials transport (mode, capacity and distance)	Research report (Spielmann et al., 2007), assumptions (Table 4)	
S3	Gasoline production and transport (mode, capacity and distance) Ethanol transport (mode, capacity and distance) Ethanol, gasoline and blends storage	Research reports (Sheehan et al. 2004; Doka 2007; Spielmann et al. 2007) Assumptions (Table 4)	Literature review
S4	Fuel use Emission data of car driving	Research reports (Kelly et al. 1996; Reading et al. 2002)	Literature review

Table 4 Hypotheses about transport activities related to ethanol life cycle

Materials	Transport mode	Capacity (tonnes)	Average distance (km)
Black locust biomass from forest to ethanol plant	Diesel lorry	16	25
Chemicals from wholesalers to ethanol plant	Diesel lorry	16	50
Solid wastes from ethanol plant to landfill	Diesel lorry	16	20
Ethanol from ethanol plant to blending refinery	Diesel lorry	32	20
Ethanol blends to regional storage	Diesel lorry	32	34

fuel use to satisfy the two challenges for the EU in terms of transport fuels that is, to promote the reduction of GHG emissions and to guarantee energy supply (CEC 2001).

3.1 Selection of the agricultural scenario

The comparative results from the LCA of the black locust production by means of two different cultivation models are shown in Table 6, where the results are presented in terms of 1 t of black locust biomass (40% moisture). According to the results, the American model based on a 5-year rotation with a total cycle of 15 years presents better environmental profile in comparison with the Swedish model. The main reason for these environmental differences is the biomass yield which is higher in the SRF scenario (16 t/ha year in the SRF instead of 12.5 t/ha year in the SRC). It is important to remark that in both scenarios, the field preparation stage does not require agrochemicals application. The absence of fertilizers application supposes that there are not diffuse emissions derived from fertilizers application, which considerably lead to contributions to impact categories such as eutrophication. Moreover, there is no excessive energy consumption associated to their production processes.

The CO_2 emitted by machinery operation in agricultural activities is offset by the CO_2 absorbed during the biomass growth. According to the result for the CC shown in Table 6, the cultivation of both crops should reduce the emission of equivalent CO_2 per tonne of biomass by nearly 1 ton. The main processes involved in the emission of GHG were field operations such as ploughing, harvesting and line harrowing.

Concerning remaining categories PO, AC and EP, it is possible to reduce the contributions up to 70% in the SRF model. According to related studies of agricultural crops production (Heller et al. 2003; Gasol et al. 2009; González-García et al. 2009a, b, 2010a, b, c), fertilizers production is an important hot spot due to SO_2 and NO_x emissions. The main contributions to these categories are emissions derived from the agricultural machineries use,

Table 5 Global inventory for lignocellulosic ethanol production

Inputs from the Technosphere			
Materials	Value	Energy	Value
Lignocellulosic feedstock (40% moisture)	98,958 kg	Electricity[a]	20,951 kWh
Vinyl acetate	28.3 kg	Steam[a]	1,169,333 MJ
Sulphuric acid	1,603 kg		
Lime	1,169 kg	Transport	Value
Diammonium phosphate	18 kg	28 tons lorry	264.24 t·km
Corn steep liquor	142 kg	16 tons lorry	393.1 t·km
Enzyme	6,062 kg		
Nutrient feed	156 kg		
Inputs from the environment			
Materials	Value		
Well water	134,508 kg		
Outputs to the technosphere		Outputs to the environment	
Materials	Value	Emissions to air	Value
Ethanol (99.5%)	16,320 kg	Vapour	168.8 tons
		Acetic acid	139.0 kg
Wastes to treatment	Value	Carbon dioxide	71.2 tons
Gypsum (to landfill)	3,895 kg	Ethanol	14.5 kg
Ash (to landfill)	779 kg	Sulphuric acid	1 kg
		Methane	1 kg

[a] From energy production process from solids from distillation, syrup and biogas

Table 6 Environmental impacts of the black locust cultivation under SRC and SRF models

Impact category	Unit	SRC	SRF
Climate change (CC)	kg CO_2 eq/tonne	−974	−985
Photochemical oxidants formation (PO)	kg C_2H_4 eq/tonne	0.035	0.011
Acidification (AC)	kg SO_2 eq/tonne	0.112	0.034
Eutrophication (EP)	kg PO_4^{-3} eq/tonne	0.023	0.007
Fossil fuels (FF)	kg coal eq/tonne	227.8	68.3
Coal	kg coal eq/tonne	1.22	0.431
Natural gas	kg coal eq/tonne	19.6	6.0
Crude oil	kg coal eq/tonne	207	61.8

specifically, harvesting and line harrowing due to NO_x emissions. The production of the machinery is also a remarkable key factor particularly in PO.

Finally, it is possible to reduce by 70% the extraction of fossil fuels when black locust biomass is produced by means of the American model due to lower energy demands required to produce higher amounts of biomass per hectare.

Therefore and according to these environmental results, it can be considered that the best option to produce black locust biomass for energy purposes is its cultivation by means of the American model.

3.2 Environmental results for E10 and E85 production

Table 7 summarizes the LCA characterisation results for each fuel, reporting the impacts of substituting CG by any of the two alternatives. Negative change implies a reduction in the environmental load compared to CG and positive value implies an increase in the environmental load.

According to the results, it is possible to obtain reductions in terms of CC, AC, EP and FF when shifting from CG to ethanol blends, although contributions to PO are increased. The higher the ethanol ratio in the blend is, the higher the change in all the categories under analysis. These results are mostly due to the replacement of gasoline by ethanol and the higher contribution from activities related to the feedstock production.

3.2.1 Climate change

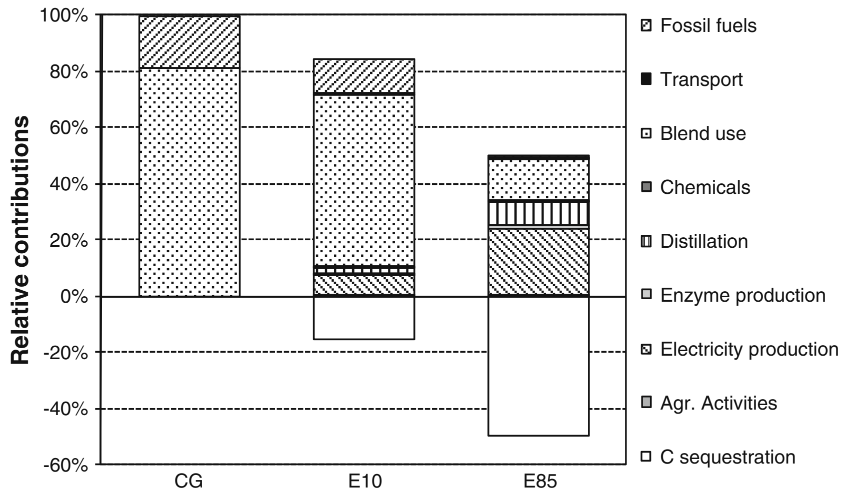
In this impact category (ISO 14040, 2006), the use of ethanol-based fuels is more advantageous than CG. The production and use of E85 can avoid up to 0.246 kg CO_2 eq per kilometre, which corresponds to a reduction in GHG of 96.6%. This result is mainly influenced by the carbon sequestered during the biomass growth which contributes to counterbalance the GHG emissions. If fertilizers are not used, no diffuse emissions will be derived from their production and use and therefore, significant reduction in the contributions to this impact category will be attained. When the blend E10 is compared with CG, no significant differences on the environmental performance (reduction up to 7.8%) are observed, essentially because the fuel economy is quite similar in both fuels and the percentage of ethanol in the blend is relatively low (only 10% *v*/*v*).

Figure 2 shows the contributions of the main processes involved in the life cycle for CG and ethanol blends. In CG and E10, the main contributor to CC is the blend use (82% and 88% of total contributions, respectively) which considers fossil and biogenic CO_2 emissions, followed by gasoline production (18% and 14% of total, respectively).

Table 7 Environmental impacts estimated per functional unit (545 km)

Category	Unit	CG	E10		E85	
			Value	Change (%)	Value	Change (%)
Climate change (CC)	kg CO_2 eq	139	128	−7.8	4.79	−96.6
Photochemical oxidants formation (PO)	kg C_2H_4 eq	0.087	0.089	+2.5	0.129	+47.5
Acidification (AC)	kg SO_2 eq	0.405	0.385	5.0	0.234	42.3
Eutrophication (EP)	kg PO_4^{3} eq	0.041	0.039	−4.9	0.024	−41.1
Fossil fuels (FF)	kg coal eq	2,089	1,955	−6.4	508	−75.7
Coal	kg coal eq	2.21	1.91	−13.8	1.11	49.8
Natural gas	kg coal eq	106	99.6	−6.1	40.7	−61.7
Crude oil	kg coal eq	1,981	1,854	−6.4	467	−75.7

Fig. 2 Contributions of the key processes to CC. *CG* conventional gasoline, *E10* ethanol in a 10% blend with gasoline, *E85* ethanol in an 85% blend with gasoline



The contribution from agricultural activities in E10 is really negligible (~0.1%) mainly due to the absence of agro-chemicals. When E85 is considered as transport fuel, the more negative processes were activities which take place in the ethanol conversion plant, specifically the electricity production and distillation. However, it is important to remark the positive effect of the CO_2 sequestered by the biomass which counteracts 98.5% of GHG emission.

The detailed analysis of the GHG emission points out the relevant role of two global warming gases: CO_2 and CH_4. The contributions of CO_2 represent the 98%, 99% and 86% of total GHG emissions for CG, E10 and E85, respectively. Concerning the CH_4, its contribution adds up to 13% in E85. The contribution from N_2O emission (mainly from agricultural subsystem) is insignificant in contrast to other related studies (Bai et al. 2010; González-García et al. 2010a) where this emission could reach 15% of total GHG emission.

3.2.2 Photochemical oxidants formation

The results (see Table 7) show an increase in the equivalent C_2H_4 emission per functional unit when shifting from CG to ethanol blends mainly due to tailpipe emissions of the FFV as well as to emissions from the ethanol production plant. Concerning the contributing emissions, in the CG, NMVOC, CO and SO_2 were the most important photo-oxidant emissions derived from gasoline production (NMVOC and SO_2) and use (CO). When E10 and E85 are used as transport fuels, there is a reduction in these emissions per functional unit. On the contrary, there is an increase in other emissions such as acetic acid and ethanol derived from the feedstock handling as well as acetalde-hyde from the blend use and as conclusion, there is an increase in the equivalent C_2H_4 emission.

3.2.3 Acidification potential

According to the results, it was possible to reduce the acidifying emissions by increasing the ratio of ethanol in the blend, although this result is completely different when compared to other related studies (Nguyen and Gheewala 2008a; González-García et al. 2009a, 2009a, b, 2010a, b, Bai et al. 2010). Traditionally, upstream activities related with the production and use of agrochemicals (e.g. ammonia emissions from N-based fertilizer production and SO_2 from P-based fertilizer production) as well as the use of the agricultural machinery (diesel combustion emissions) are the hot spots in terms of AC.

In this study, the only acidifying emissions were SO_2 and NO_x, this could decrease by the reduction in the gasoline use in transport fuel. However, the increase of ethanol in the blend also implies an increase in diesel consumed by agricultural machinery. The cultivation of the black locust with low intensive agricultural activities as well as the absence of fertilisation helps minimize the contributions from the agricultural subsystem, reducing the equivalent SO_2 emission to the atmosphere.

3.2.4 Eutrophication potential

The results obtained in the EP are really similar to the results for AP. Once again, it is possible to reduce the eutrophying emissions shifting from CG to ethanol-based fuels. The absence of fertilisation step is one of the main responsible of this environmental improvement, avoiding diffuse emissions such as NH_3 and P. If the contributing emissions are assessed more in detail, there is one major emission: NO_x in all scenarios (CG, E10 and E85), mainly derived from transport fuel use. When E10 and E85 are used as transport fuel, there is also an important contribution to NO_x emission from

agricultural machineries. Other emissions in both fuels use are phosphorous and ammonia derived from diesel production (disposal of drilling waste into landfill).

3.2.5 Fossil fuel use

Fossil fuels use was analysed and results are shown (in kilograms of coal equivalent) in Table 7. The use of ethanol-based blends instead of CG as transport fuel has beneficial effects. Although shifting from CG to E10 and E85 implies the consumption of diesel by the agricultural machineries in the black locust cultivation, less gasoline is necessary to drive the vehicle. Therefore, it should be possible to reduce up to 6.4% and 75.7% the consumption of fossil fuels when E10 and E85 are used, respectively.

Regarding the contributing fuels, crude oil is the most important, followed by natural gas and coal. The high reduction of crude oil extraction in blends with high ratio of ethanol (E85) is related to the lower ratio of gasoline used in the formulation.

The main processes which contribute to FF are the production of the gasoline in CG and E10. When E85 is used as transport fuel, there is a remarkable contribution from the production of diesel used to drive the agricultural machineries (specifically the line harrowing stage) as well as the lime required in the ethanol conversion plant (high coal requirement).

4 Discussion

The impact of the replacement of conventional transportation fuels by biofuels on the environmental impact and fossil fuel depletion is subject of fierce debate. There are a few obstacles and constraints that need to be overcome if second-generation ethanol is regarded as a potential, sustainable and cost-effective source of energy. First, the economic competitiveness of cellulosic ethanol production is highly dependent on the cost of feedstock, which can account for 35–50% of the total cost of ethanol production (Hess et al. 2007). This fact is mainly dependent on geographical (biomass yield, location, climate and/or machinery used) and political (subsidies…) factors. Furthermore, lignocellulosic biomass conversion process is still under development although this kind of biomass is abundant, inexpensive and presents no competition with food and feed (Tan et al. 2008). According to Kumar et al. (2009), the yield of ethanol from lignocellulosic feedstocks can range from 20% to 51% of the substrate weight.

Numerous LCA studies have tried to analyse the environmental benefits and weaknesses of using ethanol–gasoline-based blends from lignocellulosic biomass (Fu et al. 2003; Kemppainen and Schonnard 2005; González-García et al. 2009a, b; Luo et al. 2009a, b; González-García et al. 2010a, b; Bai et al. 2010). According to these studies, the environmental profile of ethanol-based blends in a FFV considerably depends on the selection of the system boundaries, the definition of the functional unit, the type of biomass, the allocation procedures or the methodology considered.

The yield of pure ethanol in this study is around 0.27 tonnes ethanol per tonne of dry feedstock (Table 8), which fits in with the yields obtained with other lignocellulosic feedstocks such as Ethiopian mustard, poplar, flax shives, hemp hurds and alfalfa and under an identical conversion technology (hydrolysis process and microorganisms) (González-García et al. 2010c).

With regard to the results achieved in these studies, all of them showed environmental benefits in terms of GHG emission mitigation (see Table 8) as well as fossil fuels use. On the contrary, they showed disadvantages in terms of AC, EP and PO due to the production of the feedstock because the application of agrochemicals is usually required. The production of fertilizers is a high-energy-intensive process and strongly influences the energy performance of the overall biomass production. In addition, the application of fertilizers in the soil entails the corresponding emission of diffuse emissions such as nitrate leaching, N_2O and NH_3 which considerably increase the contributions to impact categories such as EP and CC.

However, for the lignocellulosic feedstock considered in this study, the results are completely different for impact categories such as AC and EP. The black locust is a fast-growing short-rotation woody energy crop which can be cultivated under a low-input production regime, capable to grow without agrochemicals application and irrigation and it provides high yields of biomass in comparison with other related woody crops such as poplar and willow (Gasol et al. 2010). For this reason, black locust is a potential energy crop in marginal soils where food and feed crops cannot be cultivated, improving soil and water quality, increasing land-use diversity and revitalising rural economies.

With regard to CC, equivalent CO_2 emissions decreases when ethanol-based fuels are used as transport fuel. This

Table 8 Comparison between different lignocellulosic feedstocks

Feedstock	Alfalfa	E. mustard	Poplar	Flax	Hemp	Black locust
Cellulose (%)[a]	27.5	32.7	43.2	47.7	37.4	46.5
E85[b]	22,896	23,215	28,674	30,188	32,066	19,200
Biomass (kg/h)[c]	85,403	79,167	76,766	86,588	86,588	59,375
kg CO_2eq/km	0.0310	−0.1170	0.1250	0.1590	0.2270	0.0087

[a] Cellulose content expressed on dry basis

[b] E85 production expressed in kilograms per hour

[3] Dry biomass processed (0% moisture)

conclusion is in agreement with other studies on different kinds of feedstocks (Kemppainen and Schonnard 2005; Kim and Dale 2006; Luo et al. 2009a, b; González-García et al. 2009a, b, 2010a, b, c; Bai et al. 2010; Nguyen and Gheewala 2008a, b, c). However, contrarily to these studies where agricultural subsystem showed a remarkable contribution to CC, in our case study this contribution is really tiny due to the low intensive agriculture and no fertilisation stage.

Concerning the impact on PO, the results achieved are in agreement with those of other published papers, the combustion of ethanol blends reduces the CO emissions but increases the acetaldehyde emission with a high contribution to PO, increasing the photochemical oxidants formation shifting from CG to ethanol blends. Therefore, the hot spots were the tailpipe emissions and ethanol production due to the negligible contribution from agricultural subsystem.

Relating to the results for AC and EP, the contributions are smaller when shifting to ethanol blends due to the reduction of gasoline in the blend as well as the low contribution from agricultural subsystem due to the absence of fertilisation. These results are not in agreement with other related studies where the equivalent emissions were increased due to the influence of agricultural activities.

Finally, in terms of FF, the ethanol-based blends always reduce the consumption of fossil fuels independently of the biomass type being higher the reduction with the ratio of ethanol in the blend mainly due to the lower content of gasoline. The lower diesel requirement in black locust cultivation in comparison with other lignocellulosic crops, together with the non-fertilisation step, makes this woody crop in a potential feedstock for ethanol production in the future.

5 Conclusions and recommendations

The use of ethanol derived from black locust biomass cultivated in a low-input regime as liquid fuel formulated with gasoline in 10% and 85% in volume (E10 and E85, respectively) would reduce the dependence on fossil fuels, greenhouse gases emission as well as acidification and eutrophication potential. The production of lignocellulosic ethanol will require sufficient amounts of biomass available and facilities to convert biomass into ethanol within a practical distance of the feedstock production area.

LCA methodology was used in this study to evaluate the environmental profile of ethanol from black locust (*Robinia pseudoacacia* L.), a short rotation woody crop, as a transport fuel in FFVs. In addition, two scenarios of black locust cultivation (Swedish and American regimes) were assessed and compared in order to find the best model of cultivation from an environmental point of view.

The assessing results show that the use of black locust ethanol-based fuel contributes to the reduction in the impacts of CC, AC, EP and FF mainly due to the CO_2 uptake from atmosphere in black locust agriculture, low diesel requirement in agricultural activities as well as the absence of fertilising.

The results obtained in this study are comparable in some categories (CC, PO and FF) with other related LCA studies on second-generation bioethanol from lignocellulosic feedstocks. Although there are potential benefits using ethanol blends in terms of GHG and fossil fuels dependence, there is a worse impact in terms of photochemical oxidants formation. On the contrary, additional benefits are obtained in the case of black locust as feedstock such as the reduction of acidifying and eutrophying emissions. Therefore, efforts should be made to promote the production of this kind of energy crop due to its sustainable cultivation. In addition, technological development in ethanol conversion plant could help to improve the environmental profile in the ethanol-based fuels life cycle as well as it could be interesting to develop a strategic planning which allows to identify the potential regions not only in Italy but also in other European countries in order to increase the black locust biomass yield. In addition, the cultivation of SRC and SRF under low-input regimes contributes to environmental benefits and advantages in comparison with other lignocellulosic crops commonly used in the production of second-generation ethanol.

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